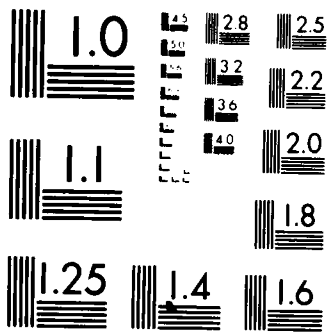
AD-A170 974 OPTOELECTRONICS IN THE PEOPLE'S REPUBLIC OF CHINA(U) 1/1
CALIFORNIA UNIV SANTA BARBARA DEPT OF ELECTRICAL AND
COMPUTER ENGINEERING J L MERZ 01 AUG 86
UNCLASSIFIED N00014-85-G-0211 F/G 20/6 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

(1) (~~2~~)

AD-A170 974

OPTOELECTRONICS
in the
PEOPLE'S REPUBLIC OF CHINA

James L. Merz
Department of Electrical
and Computer Engineering
University of California
Santa Barbara, CA 93106

During October, 1985, Professor James L. Merz spent a three week period traveling in the People's Republic of China, to visit the major semiconductor research laboratories in Beijing, Changchun, and Shanghai. In addition, Professor Merz was an invited speaker at the Third Chinese Conference on Integrated Optics held in Shanghai on 15-20 October, 1985. This report represents an assessment of current research and the potential for future research in the field of optoelectronics in China prepared as a result of those visits.

This work relates to Department of Navy Grant N00014-85-G-0211 issued by the Office of Naval Research.

86 8 1 018

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS N/A
2a. SECURITY CLASSIFICATION AUTHORITY N/A	3. DISTRIBUTION/AVAILABILITY OF REPORT Unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION James L. Merz 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION Office of Naval Research Resident Representative
6c. ADDRESS (City, State and ZIP Code) Dept. of Elect. & Comp. Engineering University California, Santa Barbara, CA 93106	7b. ADDRESS (City, State and ZIP Code) 1030 East Green Pasadena, CA 91106-2485
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Electronics Division, Office of Naval Research 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER Grant No. N00014-85-G-0211
8c. ADDRESS (City, State and ZIP Code) 800 North Qunicy Street Arlington, VA 22217-5000	10. SOURCE OF FUNDING NOS. PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT NO.
11. TITLE (Include Security Classification) SEE REVERSE	
12. PERSONAL AUTHOR(S) James L. Merz	

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
Final	FROM 8/1/85 TO 7/31/86	~~7/29/~~86 AUG. 1	23

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	Optoelectronics: People's Republic of China

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

During October, 1985, Professor James L. Merz spent a three week period traveling in the People's Republic of China, to visit the major semiconductor research laboratories in Beijing, Changchun, and Shanghai. In addition, Professor Merz was an invited speaker at the Third Chinese Conference on Integrated Optics held in Shanghai on 15-20 October, 1985. This report represents an assessment of current research and the potential for future research in the field of optoelectronics in China prepared as a result of those visits.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED XX SAME AS RPT. ☐ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL James L. Merz	22b. TELEPHONE NUMBER (Include Area Code) (805) 961-4446 22c. OFFICE SYMBOL

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE

11. OPTOELECTRONICS IN THE PEOPLE'S REPUBLIC OF CHINA

OPTOELECTRONICS
in the
PEOPLE'S REPUBLIC OF CHINA

James L. Merz
Department of Electrical
and Computer Engineering
University of California
Santa Barbara, CA 93106

INTRODUCTION

During the three-week period between October 3-24, 1985, I visited many of the major laboratories involved in research and development of compound semiconductors in the People's Republic of China:

Beijing Institute of Semiconductors
Changchun Institute of Physics
Shanghai Institute of Metallurgy
Shanghai Institute of Technical Physics
Shanghai Jiao Tong University.

The overall impression formed during this visit was a very positive one: the Chinese are building up a capability for research in important aspects of compound semiconductor materials and devices, such as MBE, reactive ion etching, HEMT, multi-quantum well lasers, etc. Their technical people are extremely intelligent and industrious; although their country is painfully underdeveloped (and the pain is most evident to the weary western traveler), they recognize the disastrous consequences of the cultural revolution, and, with windows and doors open to the west, they are working very hard to catch up in these technologies. They are also identifying markets where they might have some impact. In the last five years they have sent many visiting scholars and researchers to the United States, Europe, and Japan; although these people have not always been used most efficiently upon their return, many of them now have key positions to develop the technology they learned abroad, and are effectively doing so. The earlier emphasis on heavy industry is changing, and the most recent "Five Year Plan" includes a strong concentration in the high-tech area. [The 1986-1991

Five-Year Plan includes three high-tech areas: electronics, computer applications, and materials.] In this report I will try to assess the compound semiconductor technology that I observed in China, comment on related technologies, and make a few suggestions concerning our future interactions with the Chinese.

THE THIRD CHINESE CONFERENCE ON INTEGRATED OPTICS (CCIO'85)

This conference was held at the Shanghai Jiao Tong University, October 15-20, and was the primary reason for my trip to China. Approximately 100 participants attended from laboratories throughout China, four of whom traveled with us for 40 hours by train from Changchun to Shanghai, ample time to sample their conference contributions! Three "Visiting Firemen" from the States, including myself, were invited to give review talks:

> "The Crossing Channel Electro-Optical Modulator and Its Comparison with Other Modulators", by William S. C. Chang, University of California, San Diego.
>
> "Integrated Optoelectronic Devices for Integrated Circuits and Communications" (my talk).
>
> "Research Advances in Lightwave Communication Systems", by Tingye Li, AT&T Bell Laboratories, Crawford Hill, NJ.

A fourth invited American speaker, James H. Cole of the Naval Research Laboratory, was denied approval to attend the conference at the last minute, causing considerable consternation among our Chinese hosts. I was therefore the only speaker on the entire program to present a talk in English.

Four other invited talks were given by Chinese participants on the following subjects:

> "A Prospect for Integrated Optics", by Prof. Chen Yi-Xin, who was the conference organizer, from the Shanghai Jiao Tong University.
>
> "Materials for Integrated Optics"

"Application of Bistability in Optical Computers"

"Integrated Optics and Microfabrication"

The contributed papers were approximately evenly distributed between the compound semiconductors, and electro-optic materials such as $LiNbO_3$. In both cases there was an emphasis on the more theoretical or computational aspects of device design and evaluation, compared to actual device fabrication. This emphasis was stronger than usually observed at international conferences on integrated/guided wave optics, and reflects the current situation in Chinese laboratories. For example, there were two entire sessions on the analysis and measurement of dielectric waveguide characteristics, with papers describing complex calculations for rectangular guides, dispersion analysis, etc. Many of the measurement papers described techniques that have been in use in western laboratories for a number of years, such as loss measurements utilizing multiple prisms. However, some reasonably good results were reported for the fabrication and evaluation of semiconductor lasers, detectors, and other circuit components. For example, a low threshold (34 mA) 1.3 μm ridged waveguide double heterostructure (DH) laser was reported, and a constricted DH AlGaAs laser made by LPE was described. The state of this technology will be described in more detail below, since visits to the major semiconductor laboratories made possible a detailed discussion of recent results.

For purposes of calibration of the quantity and quality of the Chinese activity in optical communications, a very interesting talk was given at the conclusion of the conference by Professor Chang, an eminent faculty member of the Shanghai Jiao Tong University, who had just returned from the International Conference on Integrated Optics and Optical Communications (IOOC) held in Venice, Italy. Professor Chang summarized the major advances reported at IOOC, and made a number of comments to his colleagues concerning the Chinese participation at this conference. Of 209 papers presented at IOOC, only 3 were given by mainland Chinese authors, plus another that was collaborative with Professor Chen Tsai, UC Irvine. One paper was given by a student from Jilin University on coupled cavity lasers. Professor Chang exhorted his colleagues to participate in such conferences in greater numbers in order to gain direction for future research, to change the research emphasis from theoretical to applications-oriented experimental work, to work harder on the mastery of English, and to improve the quality of Chinese research!

EPITAXIAL LAYER GROWTH

Liquid Phase Epitaxy (LPE)

China is LPE country -- every lab I visited had several LPE systems, and some labs had many (e.g., Shanghai Institute of Metallurgy had at least 10). These systems are used primarily for GaAs, although some work is underway on InP-based materials. They are well-designed, and yield good material suitable for optical device application. They typically have 5 or 6 wells accomodating ≈10 x 12 mm substrates, and use a horizontal configuration with manual slider and movable furnace. To date, essentially all device results reported by the Chinese at domestic and international meetings utilize LPE material.

Molecular Beam Epitaxy (MBE)

There are currently four MBE machines in the People's Republic, and I saw three of them. They are located in the

Beijing Institute of Physics,
Beijing Institute of Semiconductors,
Changchun Institute of Physics, and
Shanghai Institute of Metallurgy.

They are all designed and manufactured in a factory in Shenyang, Liaoning Province, in the northeastern part of China. Frankly, none of them work too well at present, but the Chinese are determined to change that. The design uses sources that point upwards (the substrate points down), and six sources can be used; typically these are Ga, Al, Si, Be, and two As sources, each with a manual shutter. The vacuum system is quite good and can typically reach 2×10^{-10} Torr. Analysis equipment included is HEED, Auger electron spectroscopy, and mass spectroscopy.

The best results I heard were obtained at the Beijing Institute for Semiconductors:

Bulk GaAs mobility at 60K:	80,000 cm^2/Volt sec.
2DEG GaAs mobility at 4.2K:	320,000.

The existence of the two-dimensional electron gas (2DEG) was confirmed by the observation of Shubnikov-deHaas oscillations, but the low-temperature mobility is

nearly an order of magnitude below the current state-of-the-art. (The bulk result is reasonably good.) Furthermore, even these mobilities are not reproducible between runs, and background contamination is currently a problem. For example, the radiative efficiency of material from these machines is presently too low to make double-heterostructure lasers, and for some MBE samples, no photoluminescence is observable. (This is reminiscent of John Arthur's earliest MBE attempts at Bell Laboratories in 1967-68, when his GaP layers showed no luminescence!)

Metal-organic Chemical Vapor Deposition (MOCVD)

(The above paragraph accurately summarizes the current state-of-the-art of MOCVD in China -- zero! However, they have every intention of doing something about that.)

A Comment on Equipment

The Chinese would like to purchase commercial high-tech equipment, such as MBE and MOCVD reactors, from Japan and the western suppliers. As will be described below, they have done this to a surprising extent. However, they are limited in their ability to do so by two factors:

1. They do not have sufficient foreign currency to be able to buy as much equipment as they would like, and, more importantly,

2. Many high-tech items are included on the list of equipment that Japan and the western countries have agreed to exclude from export to China and the Soviet Union. (This is monitored through a Paris-based Coordinating Committee, COCOM.) The list includes (or included) MBE, commercial MOCVD, electron-beam exposure systems, high speed electronics such as 500 MHz oscilloscopes, streak cameras, and other sophisticated electronics equipment, as well as materials and equipment for nuclear and space development. (Note: During my visit in October I was told that this equipment was included on the list. I have subsequently learned that COCOM removed certain items from that list in October, and I am not sure if the Chinese were referring to the original or revised list. Furthermore, a story appearing in the Japan Times on December 18 stated that the United States is planning to streamline the licensing procedures, in order to "speed approval of non-strategic high-technology exports to Beijing -- now consisting of 75 percent of growing U.S.-China exports." Thus, such items as personal computers, semiconductors, fiber optics, and electronic instruments will not have to be cleared by COCOM. No list of "non-strategic electronic

instruments" was given. It appears, therefore, that although the Chinese would like to import more equipment than we will currently allow, the situation is indeed easing for them.)

RESEARCH ACTIVITIES AT INSTITUTIONS VISITED

Beijing Institute of Semiconductors

Chinese Academy of Sciences
Beijing, PRC

Institute Director: Prof. Wang Chiming

Overview

The Institute was established in 1960 as an independent institute, separate from the Shanghai Institute of Physics, with which it was earlier joined. It consists of 11 different divisions, including semiconductor materials, new technologies, surface, microwave, and optoelectronic devices, chemical analysis, LSI, CAD, and semiconductor physics. The total staff exceeds 1,000 people, with more than 500 researchers and 5 full professors. As with all of the institutes of the Chinese Academy of Sciences (Academia Sinica), students can obtain graduate degrees through the institute under the direction of full-time institute faculty. The most famous of these faculty members is Professor Huang (of Born and Huang fame). It is interesting to note that approximately 100 researchers are currently abroad, studying as visiting scholars; this is a significant fraction ($\approx$20%) of the total research staff, and suggests the importance they attach to their visiting scholar program.

I was unable to visit many of these divisions, and concentrated on the compound semiconductors. Their MBE machine was in the Division of Semiconductor Physics, and will be used to study GaAs/AlGaAs superlattices and the physics of 2DEG, as well as make quantum well devices. The semiconductor physicists are also interested in band structure of a variety of materials, electron spectroscopy, and amorphous Si, including nipi structures, which they are making with CVD.

A new laboratory building is currently under construction, which will add approximately 25,000 sq. m. to their facility. Completion date is expected to be in late 1986 (although it is my impression that construction goes very slowly in China). They currently have a 3μm photolithography capability.

I did not visit the Shanghai Institute of Physics, which has another of the Shenyang MBE machines. The two institutes have established a joint program to investigate surface physics using the two machines.

Bulk Crystal Growth

They are doing LEC growth of both GaAs and InP with two home-built pulling machines. They grow 2" GaAs semi-insulating (SI) material, and 1" InP. They claim low dislocation densities in this material. (E.g., for InP, they get etch pit densities less than 1,000 cm^{-2}, by alloying with Ga or Sb. Their GaAs results are similar with In added.)

Optical Devices

The first semiconductor laser made in China was a diffused homojunction device, made in 1963. Semiconductor laser R&D continues in the Division of Optoelectronics of Semiconductors. Their GaAs/AlGaAs DH lasers utilize proton bombardment, an obselescent technology into which they presently find themselves locked because of the requirements of a station-to-station system in use since 1979. Nevertheless, these lasers are reasonably good for proton-bombardment technology because of very uniform LPE layer growth; they have threshold currents of 40 mA and differential quantum efficiencies of 70%. I also think it impressive that they have had an optical communication system for six years, and that some cities in China have long-wavelength (i.e., InP-based) optical communication systems.

They have an extensive effort on InP/InGaAsP lasers for use at 1.3 μm, made by LPE. They are trying to improve the quality of the epitaxial layers, as evidenced by the threshold current density and device lifetime of broad-area lasers. They are also developing a variety of stripe-geometry lasers, such as ridge-waveguide lasers, double-channel planar buried heterostructure lasers, and mass-transport lasers. The latter, made by annealing mesa-etched devices at a temperature at which InP material is transported to the mesa edges, embedding the active region with lower-index material, are the most impressive, and are competitive with similar laser structures fabricated in the west: threshold current of 18 mA with extremely linear light-current curves.

Work on visible lasers is also underway, but they are way behind the U.S. and Japan in this area. They are just starting to work on avalanche photodiodes (APDs). Their future laser research plans include quantum well lasers made with their MBE machine,

and the development of InP/quaternary lasers using an MOCVD system that they hope to import if the COCOM licensing problems can be solved.

Electronic Devices

As described above, their electronic device program utilizing MBE is just now starting. Although they have observed 2DEG, their material quality is generally poor and nonreproducible. When they get the epilayer growth under better control, they also plan to work on heterojunction bipolar transistors (HBT). It should be noted that one of the researchers in the Beijing MBE group learned this technology from Professor H. Sakaki at the University of Tokyo.

New Technology

Another division of the institute is called New Technology, with plans for research in such areas as ion implantation, x-ray and electron beam lithography, and dry etching techniques. I had the distinct impression, however, that most of this work will be future activity, rather than current. For example, they expect to get a 600 keV ion implanter in the near future, and plan to work on reactive ion etching of both Si and GaAs.

The institute's photoluminescence capability is quite good, with a mode locked Argon ion laser driving a dye laser with 10 psec pulses. Research with this system is directed at very current problems, such as quantum well luminescence, and interface luminescence (such as that recently published by my laboratory) from home-grown MBE samples.

Changchun Institute of Physics

Chinese Academy of Sciences
Changchun, PRC

Institute Director: Yu Jiaqi
Honorary Director and Distinguished Scientist: Xu Xurong

Overview

This institute is half the size of the Beijing Instititute for Semiconductors, with ≈500 employees, 200 of whom are M.S. or Ph.D. equivalents. (Note that they use the word "equivalents"; in the past China has not had a degree system comparable to ours, so they go by experience. Of course, they now offer graduate degrees that they feel are comparable.) Again, there is a heavy emphasis on training abroad -- Changchun

currently has ≈40 graduate students abroad, which again represents about 20% of their researchers.

The emphasis in this institute is on solid state luminescence for displays, indicator lamps, and other solid state sources. For example, there is a great deal of work on thin film and powder displays utilizing wide-bandgap II-VI compounds such as ZnS and ZnSe. I was shown a DC panel display with yellow emission, based on the ZnS/ZnSe: Mn system, which was as bright as any produced elsewhere in the world. (This is a technology that the Japanese currently dominate.) They have also made the largest flat-panel AC electroluminescent display yet reported, 2.5 x 3.0 sq. m.

As far as compound semiconductors are concerned, the emphasis is on funda- mental knowledge, particularly of fast electronic processes in these materials. Professor Xu is internationally known in this area, and works on such problems as the generation and detection of psec and nsec pulses, fast spectroscopy, and semiconductor processes involving very fast phenomena (e.g., energy transfer). The next International Conference on Luminescence will be held in Beijing in the summer of 1987, and Professor Xu will be the conference chairman. This institute is also the headquarters for the Chinese Society of Luminescence, which edits two domestic journals on luminescence.

The other notable aspect of this institute is its establishment of a national center for characterization and analysis. This center operates in much the same way as the National Submicron Facility at Cornell, considering proposals from scientists and engineerings throughout China for research which requires this facility. Details of the equipment in this facility will be given below.

Compound Semiconductors

Most of the semiconductor work in Changchun is on optical devices, with heavy concentration on visible lasers and LEDs. Japan currently has 70-80% of the world's market of LEDs (over 3 billion LEDs are made in Japan annually), and China wants its share.

The AlGaAs/GaAs system is the principal material chosen for visible LEDs, with 35% Al in the active layer, corresponding to an emission wavelength of 0.66 μm. They have routinely achieved efficiencies of 2-3%, which is satisfactory, but have not succeeded in reducing the cost to a competitive level. They are also working on GaP:N, for which they can also make good quality but too expensive diodes, and on

GaN, for which they, along with the rest of the world, have been unable to solve the type-conversion problem.

Another subject of some interesting work at Changchun is that of coupled-cavity amplifiers using Fabry Perot resonators, with GaAs lasers supplied by Shanghai or Beijing. (Note that they are not yet making semiconductor lasers at Changchun, although that is one of their goals.) They have achieved gain of 25 dB at 0.85 μm with this configuration, and are now initiating a new project on a traveling-wave amplifier using phase matching.

Changchun is one of a small number of laboratories in the world (along with GM and Lincoln Lab in the U.S.) working on PbSnTe infrared lasers. They currently make infrared lasers operating between 10 and 13 μm (at T=23K), tunable by varying injection current, pressure, or magnetic field, and are trying to make double-heterostructure devices (which has already been done in the U.S.), which would have a higher operating temperature.

At the other end of the spectrum, there is a significant effort on wide-bandgap II-VI compounds such as ZnSe, with the hope of solving the type-conversion problem to make efficient p-n junctions for blue LEDs. They have made MIS structures which emit blue light under forward bias,with good electroluminescent spectra (i.e., no deep-level emission), and MS (metal/semiconductor) devices which emit yellow light under reverse bias. However, the efficiencies for blue emission are still far too low to be useful, $\approx 10^{-5}$.

The institute is in the midst of a reorganization which suggests the importance they attach to compound semiconductors for future device work. Two departments will be combined, involving semiconductor lasers and integrated/guided-wave optics using III-V compounds and $LiNbO_3$ (dielectric waveguides, acousto-optic interactions, nonlinear optics, periodic structures). The integrated optics work will be directed by Mr. Yuan Yourong, who had worked as a visiting scholar in my laboratory in Santa Barbara for more than two years. A separate department will work on the related materials problems, such as crystal growth, optical and electrical properties, defects and impurities, and basic physics of these materials.

National Center for Characterization and Analysis

The facilities already assembled for this center are quite impressive. Much of it has been bought in the U.S., Japan, or western Europe; they tend wherever possible to buy complete systems for characterization and analysis. Below I will describe this facility in some detail, not because such detail is important for its own sake, but to give the reader an accurate impression of the scope of this center and the level of sophistication involved.

1. Room Temperature Photoluminescence: Chinese-built Ar^+ ion and dye laser system with 1-meter double grating monochromator.

2. Low Temperature Photoluminescence: Nitrogen-pulsed dye laser, Oxford liquid helium cryostat with 7-Tesla superconducting magnet, Spex double monochromator, Products for Research photomultiplier coolers, all under computer control.

3. Raman Spectroscopy: Jobin-Yvon JY T-800 complete Raman system with sample refrigeration system, Ar^+-laser excited dye laser, He-Ne laser, Nd:YAG laser, photon counting system, uniaxial stress. Best Raman system in China.

4. Nanosecond Fluorescence Time Resolution System: Flash lamp, large-aperture monochromator, photon counting system with time correlation.

5. Picosecond Time Resolution System: Chinese mono- chromator and two separate laser systems:

   (a) Mode-locked Spectra Physics Model 171 Ar^+ ion laser with four dye lasers, and

   (b) High-power Lambda Physik excimer laser plus dye laser, with Kerr cell switch driven by Ar^+ ion laser.

6. Electron Paramagnetic Resonance: Varian "E-Line Century Series" complete system.

7. X-Ray Diffractometer: Rigaku rotating anode and double crystal diffractometers.

8. Scanning Electron Microscope: Hitachi 50 keV SEM.

9. Ion Implantation: Home-built 400 keV machine with extremely flexible source, capable of providing beams from solid, liquid, or gas materials, covering most of the periodic table.

Shanghai Institute of Metallurgy
Chinese Academy of Sciences
Shanghai 200050, PRC

Director: S. C. Zou

Overview

This institute was established in 1929 to work on classical, macroscopic problems of metallurgy. In recent years the focus of the institute's research has changed, and it has experienced great growth. Since the early 1960s, the emphasis in this institute has shifted from metallurgy to new materials such as semiconductors and magnetic materials, with emphasis on both discrete devices and integrated circuits. The size of the institute has also changed significantly, from a total staff of 70 in 1952, to over 1,200 at present. Of these there are approximately 750 scientists and technicians, including 40 professors and associate professors, and 80 graduate students. Again, many of their people are studying abroad; at present there are 5 Ph.D. students studying outside of China.

Although the primary support received by all institutes of the Chinese Academy of Sciences is the federal government, this institute is developing strong relationships with manufacturing companies in and around Shanghai, and, to a much lesser extent, foreign companies. In particular, there are two optical fiber factories in Shanghai, and one factory manufacturing terminal and optical communications equipment; the Shanghai Institute of Metallurgy is providing the R&D support for this manufacturing activity, with a strong attempt to transfer technology to these factories. In fact, my host for this visit, Professor Pan Huizhen, a reknowned scientist who is in charge of the optoelectronics research at the institute, spends much of her time developing relations

with industry for research support and technology transfer. She and I agreed that we had much in common!

There are now three main areas of emphasis in the institute:

1. Si LSI Microelectronics, started in 1965. They have transfered to a local factory their 16 k EPROM and 4 k CMOS SRAM, and are currently working on a 16 bit microprocessor.

2. Functional Materials and Devices. This is where compound semiconductors fit in, with a large effort on optical devices and a small but growing effort on HEMT. Other subjects of investigation in this section are magnetic bubble material, hydrogen storage material for the purification of hydrogen for semiconductor applications, and semiconductor sensors and transducers.

3. Corrosion. (And I heard no more about corrosion.)

Bulk Crystal Growth

The LEC crystal pullers were designed and built in this institute. They are currently growing 1" boules of InP and semi-insulating GaAs (either undoped or Cr-doped). Etch pit densities are of order 10,000 cm^{-2}.

Horizontal Bridgeman is also used for GaAs doped with Si, Cr, and Te, and for high-purity GaAs. Etch pit densities are a factor of 10 less than LEC (1,000 cm^{-2}), and they can control stoichiometry better by varying the As pressure. They have compared the microwave properties of FETs made on both substrates, and find them superior for devices made on HB. The problem with this material, however, is that the substrates are too small.

MBE

Their MBE machine was received from Shenyang only a month earlier, so they have not yet grown any layers with it. However, they have been able to reach a vacuum of 10^{-10} Torr. Some layers were grown with this machine by Mrs. Li, the MBE group leader, at the factory, which resulted in a paper presented at the 1984 MBE workshop in San Francisco. It is interesting to note, by the way, that Mrs. Li was a visiting scholar with Professor A. Milnes in Carnegie Mellon, where she learned MBE

technology; she is another example of a Chinese scholar who is being well used by her institute to initiate an MBE program in Shanghai.

Plans for this machine include the growth of GaAs on Si substrates, growth of GaAs on Ge on Si substrates, and GaAs/AlGaAs (on GaAs substrates) for HEMT and optical devices.

High Speed Electronic Devices

During the "shake-down" period for their MBE machine, the electronic device group has started to "practice" HEMT fabrication with material supplied by Carnegie Mellon -- no performance data were mentioned. However, it is clear that they intend to make HEMT research a significant activity, and already have 10 researchers in their new HEMT group. They have also worked on a variety of other devices, including GaAs MESFET with tungsten silicide gate, 18 GHz GaAs switch, GaAs Varactor with f>400 GHz, Gunn Diode operating at 8.6 mm, and a dual-gate FET with transconductance of 20-30 mS/mm.

Optoelectronic Devices

The Institute is working on a variety of optoelectronic devices, and has achieved respectable performance for several of them. These devices are made by LPE. Results will be summarized only briefly here.

1. High Efficiency GaAS/AlGaAs Solar Cells. They routinely fabricate devices of 1 sq. cm area with efficiencies of 16-17% achieved routinely, 20% maximum. This compares favorably with the best reported world-wide: maximum 21-22%, but typical values of 12-15%.

2. High Radiance GaAs LEDs. They have developed LEDs in both the edge-emitting configuration for higher speed, typically 50-70 MHz, up to a maximum exceeding 100 MHz, and the Burrus configuration for high power output. They have been able to couple 100 μW into optical fibers, which is modest compared to the state-of-the-art (e.g., Fujitsu in Japan and Codenol in the U.S., both of whom can couple 150-200 μW into fibers.) These devices are now manufactured in a Shanghai factory.

3. InP LEDs. Since 1981 they have been working on InP LEDs at both 1.3 and 1.55 μm. They have achieved 1 mW output power, and have coupled 50 μW into

an optical fiber. They have now set up a pilot line for the small scale production of these devices.

4. InP/InGaAsP Lasers. These devices are currently under development.

5. GaInAs/InP PIN Photodetectors. These devices currently work at frequencies up to 30 MHz -- the goal is 50 MHz. Hybrid integration with GaAs FETs has been achieved.

6. Integrated Optics. In the GaAs/AlGaAs system, they have been working on etched mirror lasers in parallel with my work, and have achieved comparable results. They are currently trying to make stripe-geometry devices with etched mirrors, but efficiency is low for mirrors made by wet chemical etching. They are therefore building up a capability for reactive ion etching. A second LPE furnace is being used for the InP system, for which they are working on the integration of an optical source (initially a LED, later a DH laser) with a heterojunction bipolar transistor (HBT). A third LPE system is used for InGaAs detectors. The ultimate goal for much of this work is a monolithically-integrated repeater for long distance optical communications.

Characterization and Processing Capability

The institute appears to be reasonably well equiped. An important facility is the Rutherford Backscattering (RBS) laboratory, with a 2 MeV accelerator for RBS and channeling, manufactured by National Electrostatic Corporation in Madison, Wisconsin. They are currently studying the formation of silicides on Si, and the interface between GaAs and Ge; future plans include superlattice studies.

A new reactive ion beam etching system (RIBE) has just been developed in this institute. They use CF_4 as the reactive gas, and can produce a 10 cm beam diameter with energies between 100 and 1,000 eV (below 100 eV the beam becomes unstable).

Another research program in the Institute of Metallurgy involves the use of lasers and flash lamps for annealing implant damage and recrystallizing amorphous material. A Q-switched ruby laser, both Q-switched and continuous wave (CW) Nd:YAG lasers, and a CW Ar^+ ion laser are all used to anneal the damage produced by B and P implants into Si, and Si implants into GaAs. These results are compared with rapid thermal annealing (RTA) using incoherent lamps for short time cycles. Much work on this subject has been carried out in Japan and the west for the last 8-10 years, where it

has generally been found that RTA gives superior device results compared with laser annealing, and I did not hear of any remarkable new results at this institute. However, they are working in some of the areas that are considered in the west to be most promising, such as the laser alloying of Au/Ge/Ni contacts on GaAs, and the use of scanned CW lasers to regrow polycrystalline Si on insulators (SOI). For example, they have produced single crystal grains as large as 30 μm, and have formed n-channel and p-channel MOSFET devices, and complementary MOS devices, on these grains. Other characterization equipment includes Deep Level Transient Spectroscopy (DLTS), and several optical techniques: photoluminescence, photo-Hall effect, photocapacitance, and photo induced transient spectroscopy (PITS). For DLTS they have two systems, one Japanese and one Chinese, with better results obtained from the former.

<u>Shanghai Institute of Technical Physics</u>
Chinese Academy of Sciences
420 Zhong Shan Bei Yi Road
Shanghai, PRC

Associate Director: Professor Liu

Overview

This institute was founded in 1958 in the fields of solid state physics and electronics. They currently have approximately 500 people in total, with 10 professors and 70 graduate students, mostly M.S. Since 1964 the emphasis has been Infrared Physics and Technology. There are three general areas of research:

1. IR elements and devices, with work on Hg-doped Ge, InSb, HgCdTe, thermal IR detectors, CCD devices, and materials for IR optics. Some of this work will be described below.

2. Applications to remote sensing, such as airborn multispectral scanners, and two-dimensional imaging systems for medical and military applications. I think that this activity was extremely impressive; for example, I saw a thermal imaging system for medical diagnosis which had very sophisticated software, and which was comparable to equipment produced in the U.S. They are also doing some excellent work on multispectral scanners. In one activity they are collaborating with William Collins, President of Geophysical Environmental Research, Inc. (GER), who makes a 64 band airborne spectrometer that does not scan. The airborne scanner made in Shanghai has only 6 bands, but obtains comparable results. The Chinese consider

remote sensing to be an important field, and I was told they have launched 16 satellites to date (but I could not be told the location of their launching site, since they are not publicized.) They also have graduate students in U.S. university departments known for a strength in remote sensing, of which UCSB is one.

3. Infrared Physics, with emphasis on the physics of very narrow bandgap semiconductors, and far infrared spectroscopy and detection.

One of the strengths of this institute is its experimental capability for investigating the properties of infrared materials. In particular, they have an excellent facility for Fourier Transform spectroscopy, infrared absorption, photoluminescence, and Raman scattering. This spectroscopy laboratory has been designated an OPEN LABORATORY, open to all researchers from China <u>and abroad</u>. (I was encouraged to come back as soon as possible.) The Chinese Academy of Sciences will entertain proposals from any investigators to do research using these facilities, and will fund those judged to be superior.

Another interesting aspect of this institute is the creation of a new department for technology transfer, which has thus far exported infrared devices in small quantities. For example, they have shipped several dozen pyroelectric detectors, which are considered to be superior devices on the world market, to West Germany. Another example of successful technology transfer from this institute to industry is the use of Si photodiodes in the budding Chinese camera industry.

My host for this visit was the Associate Director of the Institute, Professor Liu, who spent a year in Santa Barabara as a visiting scholar with Professor Walker in the Department of Physics.

Si Devices

One major area of activity in this institute is the development of Si detectors and CCD imaging arrays. They are making both 1 and 2-dimensional CCD arrays. A principal researcher involved in this research, Mr. Wu Zuoliang, was a visiting scholar in my laboratory between 1980 and 1982.

Thus far their CCDs have been developed for visible light imaging, but they are working on Si photodiodes with good UV response. The detectors used for these imaging arrays are Silicide Schottky Barrier devices, with a 1 μm depletion region, and a Pt silicide contact of thickness $\approx$20-100Å to extend the device sensitivity to

$\approx$6 μm. However, their devices have a lower efficiency than those reported in the U.S.

III-V Compounds

There is little work on III-V compounds except for the narrow bandgap material InSb, used for infrared detectors. Their material has very low background carrier concentrations, $< 10^{14}$ cm^{-3}, which they export to other countries since it is believed to be the highest purity material available worldwide. They achieve this by multiple gas transports ($\approx$500 times) of the starting material. The wafers are grown by Czochralski (not LEC since there are not serious pressure problems as with wider-bandgap III-Vs), and have etch pit densities < 100 cm^{-2}.

Physics of Infrared Materials

The Institute has a strong infrared measurement capability, and they are using it for detailed studies of HgCdTe and other narrow-bandgap materials. Principal equipment acquisitions are a Perkin Elmer IR Spectrophotometer (Model 983), which is a new, modern instrument with computer processing, and a Nicolet Fourier Transform Spectrometer (Model 200SXV) complete system. This equipment is being used to carry out a systematic study of the infrared absorption of HgCdTe. They can measure absorption coefficients as high as $\approx$3,000 cm^{-1} by polishing samples to thicknesses < 10 μm. By fitting their data to the Kane model, they believe they have the most accurate measurement of the energy gap of $Hg_{1-x}Cd_xTe$ as a function of composition for x in the range $0.165 \leq x \leq 0.4$. They also determine the intrinsic carrier concentration and effective masses; they find electron carrier concentrations less than 10^{14} cm^{-3} and measure $m_{hh} = 0.55\ m_o$. I believe this work to be of high quality, on a subject which is currently receiving heavy funding from the Department of Defense in the U.S.

The Fourier Transform Spectrometer is being used for the study of local modes in a number of materials such as GaAsP, CdMnTe, Fe-doped Si, and HgCdTe. In addition, they have identified shallow impurities in some of these materials, such as the shallow Li acceptor in CdTe.

Two other impressive laboratories (which I understand are part of the "Open Laboratory" described above) are a photoluminescence (PL) laboratory and Raman scattering. Both labs have new equipment recently bought from the west. The PL lab uses a Chinese argon ion laser, Jobin Yvon spectrometer with 7 gratings covering the

spectral range from UV to 14 μm, Oxford Instruments transfer-type liquid He cryostat, photon counting and phase sensitive detection. They are currently using this system to study the surface treatment of CdTe, for use as a substrate for HgCdTe epitaxial layers. The Raman lab has a Coherent Radiation 5W argon ion laser, SPEX double monochromator with complete data processing system, cooled photomultipliers, etc. The system is brand new, and is just being used for Si investigations.

Shanghai Jiao Tong University
1954 Hua Shan Road
Shanghai 200030, PRC

Host: Prof. Chen Yi-Xin

Overview

Professor Chen was the organizer of the Chinese Conference on Integrated Optics, and as such was my host in Shanghai, providing the formal invitation for my visit to China. He is a professor of the Department of Applied Physics in the Jiao Tong University, and its former chairman. He has been extremely active in developing the technological capability of this department, and is making significant progress; the department, and in particular his program, are focusing on important problems, but progress is impeded by serious obstacles. Prof. Chen is very knowledgeable concerning western science and technology, but university funding for research and equipment appears to lag significantly behind the support available for the research institutes within the Chinese Academy of Sciences (such as those described above). Also, some of the equipment he needs is excluded for export to China by COCOM. Professor Chen was a visiting scholar for one year at UC San Diego with Prof. William Chang; his research area is optoelectronics.

The Shanghai Jiao Tong University is the primary technology-oriented higher educational facility in Shanghai (and, for that matter, one of the best in China), whereas basic arts and science are emphasized at Fudan University. American analogues might be MIT and Harvard, respectively.

Optoelectronics

Professor Chen is working on a number of important problems, but in each case he is having difficulties due to equipment limitations.

1. Heterojunction phototransistors, using InP/InGaAsP grown by LPE. Their current problem is a background carrier concentration that is too high (7×10^{17} cm^{-3}), so that dark current is excessive.

2. Gratings. They are modifying a Hitachi Model S450 SEM to write chirped gratings (i.e., gratings with changing period). This work is being done in collaboration with another researcher who spent time as a visiting scholar in the west modifying a SEM for e-beam exposure.

3. $LiNbO_3$ Fabry-Perot modulator, with Ti-diffused waveguides. This device works at f>600 MHz. They want to butt-couple it to GaAs DH lasers, but have stability problems due to the coupled cavities. They are also planning to work on stepped $\Delta\beta$ directional couplers.

4. Ge Avalanche Photodiodes. They use a guard-ring configuration by implanting Be, but their early devices have relatively low gain: 5-10.

Jilin University
Changchun, PRC

Visitor: Professor Gao Ding-san

Professor Gao is Head of the Semiconductor Department of the Jilin University. Although time did not permit my visiting his department, he arranged to visit me during my stay in Changchun, and we were able to discuss optoelectronics research in our respective institutions. Professor Gao was accompanied by two colleagues, Professor Liu, who is in charge of device physics, and Professor Zhang, a former research scholar at Brown University who is now interested in semiconductor processing.

Professor Gao described Jilin as a major semiconductor center. They work on lasers (both GaAs and InP) using an LPE system that was commercially produced in China (and which gave them much trouble at first). They work on integrated optics and OEIC, trying to integrate lasers with FETs. They plan to make DFB lasers, and are

setting up reactive ion etching (which Professor Zhang studied at Brown). Professor Liu has worked on superlattices from a theoretical point of view, doing LCAO calculations. In general, I got the impression that they have very ambitious plans, but are only beginning much of this work. As I saw in so many other laboratories, Professor Gao described a Chinese shift in policy which allows them to purchase laboratory equipment from the west, and they are doing so at Jilin.

Zhejiang University
Hangzhou, PRC

Host: Professor Wang Ming-Hua

Professor Wang is a professor in the Department of Radio and Electronic Engineering, and currently serves as Department Chairman. He invited me to come to Hangzhou for several days to lecture on optoelectronics, since that is one of their four areas of current research, and one that they intend to expand in the future. (The other three areas are Communications, Microwave and Electron Physics, and Si ICs.)

They are presently assembling several characterization and fabrication laboratories (including a clean room which is under construction), much of which is used for instruction. Professor Wang appears to be the most active faculty member, and is establishing a program to design and build a directional-coupler modulator for use at1.2 GHz. This is a technology he learned as a two-year visiting scholar at the University of Tokyo with Professor K. Tada. He has just received a grant from the Ministry of Education to purchase an e-beam evaporator, magnetron sputtering system, mask aligner, LPE system, optical isolation table and device testing system, and high frequency oscillator.

Hangzhou also has a Jiao Tong University, with interests in optical communications. Dr. Tynge Li of Bell Laboratories was invited to present a series of lectures there on optical communications and systems. The other notable fact about Hangzhou is its beauty -- West Lake and surroundings are simply exquisite, giving rise to an old Chinese saying:

In Heaven there is Paradise --
On earth there is Suzhou and Hangzhou.

We never got to Suzhou, which gives us yet another good reason to return to China!

CONCLUDING COMMENTS

I hope that I have left the reader with an impression that a dynamic growth in compound semiconductor research and development is taking place right now in the People's Republic of China. They are just beginning to work in the important areas, such as MBE, RIE, MQW lasers, MESFET ICs and HEMT technology, but they have not accomplished a great deal in these areas. They have been doing good, solid research in optoelectronics for a number of years, and they plan to expand this work considerably; many new laboratories, including clean rooms, are presently under construction. Due to a major shift in policy in China, doors are being opened to the west, and the Chinese are importing as much high-technology equipment as they possibly can. The U.S. government appears to be decreasing the barriers for at least some of this equipment, but there are still severe limitations on the Chinese. It has been my impression, formed during this three-week tour, that the Chinese are making very good use of their visiting scholar and study abroad program, although there are, of course, some counter examples. Most recently they seem to be sending younger men and women, including larger numbers of students, who will be the leaders to tomorrow. They are also increasingly asking their hosts for financial support for these students and researchers.

The image of a "sleeping giant" slowly awakening is perhaps a good one, and when we consider the size of China's population, the implications of this are enormous. In my report I have emphasized the modern laboratory facilities they are constructing, as well as described their current progress in optoelectronics, because the build-up of experimental capability with sophisticated measurement equipment suggests their potential for the future. In addition, there has been an emergence of consumerism and free enterprise throughout their country. For example, the government has allowed people to establish private business enterprises in the last few years, and my Chinese hosts and friends frequently commented that these shopkeepers and businessmen were "becoming rich." When we arrived at Beijing airport, we found it almost impossible to get our baggage to the customs inspection stations because of the incredible piles of Japanese color television sets that Chinese tourists and businessmen were bringing back from Tokyo and Hong Kong! I have read recently that the Chinese government thinks this is getting out of hand and is tightening the restrictions, but I would guess this is simply an oscillation about a curve which will continue to grow for many years, especially if encouraged by the west.

As the Chinese overtures to the west increase, as I expect they will, the U.S. will have to decide whether to help them move squarely into the modern age or not. It seems to me that the prospect of this huge socialist nation becoming increasingly friendly with

us, and being more strongly influenced by our technology and way of life, is a very positive one, particularly when one keeps in mind their more than one billion potential consumers! For example, Fujitsu Electric recently concluded contracts for 2 billion yen to supply instrumentation and technical information to factories and plant engineering offices in China, with the hope of obtaining twice that in contracts with China next year. That hardly scratches the surface of the profit potential that this huge, developing country represents. It is my hope that interactions and collaborations between the United States and China on the technical level will also increase in coming years.

ACKNOWLEDGEMENT

I would like to thank Professor Chen Yi-Xin of the Shanghai Jiao Tong University and Professor William Chang of the University of California, San Diego, for making this trip possible; all of the directors and administrators of the institutions visited for their unsurpassed hospitality; Dr. George Wright of the Office of Naval Research, Far East Liaison Office, for his help with this report. Mr. Yuan Yourong of the Changchun Institute of Physics was my guide for the entire trip in China, and he translated most of my seminars and talks. His assistance was indispensible!

END
DTIC
9-86